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F. Parrenin[1], J.-M. Barnola[1], J. Beer[2], T. Blunier[3], E. Castellano[4], J. Chappellaz[1], G. Dreyfus[5], H. Fischer[6], S. Fujita[7], J. Jouzel[5], K. Kawamura[8], B. Lemieux-Dudon[1], L. Loulergue[1], V. Masson-Delmotte[5], B. Narcisi[9], J.-R. Petit[1], G. Raisbeck[10], D. Raynaud[1], U. Ruth[6], J. Schwander[3], M. Severi[4], R. Spahni[3], J. P. Steffensen[11], A. Svensson[11], R. Udisti[4], C. Waelbroeck[1], and E. Wolff[12]

[1]Laboratoire de Glaciologie et Géophysique de l'Environnement, CNRS and Joseph Fourier University, Grenoble, France
[2]Department of Surface Waters, EAWAG, Dübendorf, Switzerland
[3]Climate and Environmental Physics, Physics Institute, University of Bern, Bern, Switzerland
[4]Department of Chemistry, University of Florence, Florence, Italy
[5]Laboratoire des Sciences du Climat et de l'Environnement, IPSL/CEA/CNRS/UVSQ, Gif-Sur-Yvette, France
[6]Alfred-Wegener-Institute for Polar and Marine Research, Bremerhaven, Germany
[7]National Institute of Polar Research, Research Organization of Information and Systems (ROIS), Tokyo, Japan
[8]Center for Atmospheric and Oceanic Studies Graduate School of Science, Tohoku University, Sendai, Japan
[9]ENEA, C. R. Casaccia, Roma, Italy
[10]CSNSM/IN2P3/CNRS, Orsay, France
[11]Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
[12]British Antarctic Survey, Cambridge, UK

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Abstract. The EPICA (European Project for Ice Coring in Antarctica) Dome C drilling in East Antarctica has now been completed to a depth of 3260 m, at only a few meters above bedrock. Here we present the new EDC3 chronology, which is based on the use of 1) a snow accumulation and mechanical flow model, and 2) a set of independent age markers along the core. These are obtained by pattern matching of recorded parameters to either absolutely dated paleoclimatic records, or to insolation variations. We show that this new time scale is in excellent agreement with the Dome Fuji and Vostok ice core time scales back to 100 kyr within 1 kyr. Discrepancies larger than 3 kyr arise during MIS 5.4, 5.5 and 6, which points to anomalies in either snow accumulation or mechanical flow during these time periods. We estimate that EDC3 gives accurate event durations within 20% (2σ) back to MIS11 and accurate absolute ages with a maximum uncertainty of 6 kyr back to 800 kyr.

1 Introduction

The EPICA project has provided two records in East Antarctica, one at Dome C (EDC, EPICA community members, 2004), and one in the Dronning Maud Land area (EDML, EPICA community members, 2006). The completion of the Dome C core was delayed when the first drilling became stuck at 788 m in 1999. This shorter EDC96 core provided 45 kyr of paleoclimatic reconstructions (e.g., Jouzel et al., 2001; Monnin et al., 2001). The next EDC99 drilling was voluntarily stopped at a depth of 3260 m, about 15 m above bedrock, above which seismic soundings suggest the presence of melt water. EDC provides the longest in time ice core record available so far, with so far ∼740 kyr records of Antarctic temperature (EPICA community members, 2004) and chemical impurities in Antarctica (Wolff et al., 2006), and ∼650 kyr records of atmospheric composition (Siegenthaler et al., 2005; Spahni et al., 2005). All these records are currently being extended to 800 kyr.

An accurate age scale is the basis for the interpretation of paleoclimatic records. We distinguish different types of accuracies. First, age scales need to be accurate in terms of absolute ages: we want the estimated age at a certain depth to be as close as possible to the real age (with an accuracy expressed in yr). This absolute accuracy is crucial when examining the phasing of two absolutely dated paleoclimatic records, and with insolation variations calculated by modelling of planet movements in the past (Laskar, 1990). For example, the insolation/climate phase relationship has been studied for terminations I and II thanks to accurate absolute age scales (Jouzel et al., 1995; Henderson and Slowey, 2000).

Correspondence to: F. Parrenin
(parrenin@ujf-grenoble.fr)

Second, sequences of events can be analysed in detail without absolutely perfect age scales, provided that the studied records are stratigraphically linked. Here a relative age scale, (with an accuracy expressed in years) suffices. For example, the phasing between Antarctic temperature and CO_2 variations during the last deglaciation has been obtained from the Dome C core by estimating the ice/gas bubbles age difference (Monnin et al., 2001). Other examples include the phasing between Greenland and Antarctic temperature during the last glacial period obtained by a synchronisation of those records with the CH_4 atmospheric composition, which varies in phase at both poles (Blunier et al., 1998; EPICA community members, 2006). Third and finally, the last important accuracy is in the duration of climatic events (expressed in per cent). Indeed, this duration is characteristic of the climatic mechanisms involved, and will impact the frequency analysis of the records. We can cite as an example the duration and pacing of the so-called Dansgaard-Oeschger (D-O) events during the last glacial period which has been extensively studied (e.g., Schulz, 2002).

In the absence of radiochronologic constraints, numerous methods have been developed to date ice cores. They fall into 4 categories: (1) counting of layers representing a known time interval, e.g. annual layers, (2) ice flow modelling, (3) wiggle matching on other precisely dated time series, in particular insolation variations, and (4) use of climate independent age markers, like volcanic eruptions.

Ice flow modelling has been historically used to date ice cores from Greenland and Antarctica. A one-dimensional flow model was first applied to Camp Century (Dansgaard and Johnsen, 1969), and later to GRIP (Johnsen and Dansgaard, 1992; Johnsen et al., 2001). The Camp Century, Dye-3 and GISP2 cores were also interpreted by matching the oxygen 18 isotope record of ice or air bubbles to the SPECMAP stack (Dansgaard et al., 1985; Bender et al., 1994), which is itself orbitally tuned. The GISP2 core was also dated with annual layer counting (Alley et al., 1997). In Antarctica, two-dimensional flow models were applied to the along-flow (non-dome) drilling sites of Byrd (Johnsen et al., 1972) and Vostok (Lorius et al., 1985; Parrenin et al., 2004). Annual layers were counted back to the LGM at Byrd (Hammer et al., 1994). The Vostok ice core has also been dated by matching to the orbital SPECMAP scale (Bender et al., 1994), or directly to insolation variations (Waelbroeck et al., 1995; Shackleton, 2000). More recently, one dimensional flow modelling controlled by other dating methods was applied to the EPICA Dome C ice core (EDC1, Schwander et al., 2001; EDC2, EPICA community members, 2004) and Dome Fuji ice cores (Watanabe et al., 2003).

All the above dating methods have advantages and drawbacks. Layer counting (Andersen et al., 2007) and ice flow modelling (Parrenin et al., 2006) are accurate in terms of event durations because they are based on the evaluation of the annual layer thickness. On the other hand, errors cumulate and the accuracy on absolute ages decreases with depth. The new layer-counted chronology for Greenland (GICC05, Vinther et al., 2006; Rasmussen et al., 2006; Andersen et al., 2006; Svensson et al., 2006) uses an improved multi-parameter counting approach, and currently extends back to around 42 kyr BP with a maximum counting error of 4 to 7% during the last glacial period. Unfortunately, layer counting is not feasible in central Antarctica where annual cycles are barely distinguishable (Ekaykin et al., 2002).

Comparison of paleoclimatic records to insolation variations (so-called orbital tuning methods) are generally applicable to a whole ice core, as long as the stratigraphy is preserved (e.g., Martinson et al., 1987; Dreyfus et al., 2007). On the other hand: (1) the accuracy in terms of event durations is poor, (2) the accuracy in terms of absolute ages is limited by the hypothesis of a constant phasing between the climatic record used for the orbital tuning procedure and the insolation variations (and, by definition, does not allow one to infer this phasing). The advantage is that the achieved accuracy does not decrease with depth (assuming the underlying mechanism stays constant). As a consequence, it is currently the most precise method to date the bottom of deep ice cores. Recently, the search for local insolation proxies in ice cores as, e.g. the O_2/N_2 ratio (Bender et al., 2002; Kawamura et al., 2007) or the air content record (Raynaud et al., 2007) has opened new prospects for eliminating the reliance on this hypothesis of constant insolation/climate phase, potentially allowing an accuracy within 1 kyr to be achieved in the coming years.

Precisely dated volcanic horizons provide important age markers. This is the case for the last millenium (Traufetter et al., 2004), but beyond that limit, only a few of them have accurate absolute ages (Narcisi et al., 2006). In Antarctic ice cores, comparison to absolutely dated paleoclimatic records is particularly relevant for the dating of the D-O events, which have been accurately dated in several archives, and whose rapid transitions can be localized with a high accuracy in the Antarctic CH_4 record. The transfer of those age markers to the Antarctic ice matrix requires the evaluation of the ice/gas age difference with a firn densification model (e.g., Goujon et al., 2003, and references therein).

In this article, we present EDC3, the new 800 kyr age scale of the EPICA Dome C ice core, which is generated using a combination of various age markers and a glaciological model. It is constructed in three steps. First, an age scale is created by applying an ice flow model at Dome C. Independent age markers are used to control several poorly known parameters of this model (such as the conditions at the base of the glacier), through an inverse method. Second, the age scale is synchronised onto the new Greenlandic GICC05 age scale over three time periods: the last 6 kyr, the last deglaciation, and the Laschamp event (around 41 kyr BP). Third, the age scale is corrected in the bottom ~500 m (corresponding to the time period 400–800 kyr BP), where the model is unable to capture the complex ice flow pattern.

In Sect. 2, we first present the different age markers that can be found in the EDC ice core. We then describe in Sect. 3 the construction of EDC3. In Sect. 4, we compare it with other age scales from the late Quaternary. Finally, we discuss the accuracies of this new time scale in Sect. 5.

In this paper, the notation "yr BP" refers to "years before AD1950".

2 Age markers

In this section, we describe the dated horizons (so-called age markers) that can be derived from the EDC ice core.

2.1 Dated volcanic eruptions during the last millenium

Using sulphate data (Castellano et al., 2005), several volcanic eruptions of known age have been identified in the EDC96 ice core during the Holocene. Among these, only a few of the most recent are independently absolutely dated (Traufetter et al., 2004): Krakatau[1], 8.35 m, AD1884±1; Tambora, 12.34 m, AD1816±1; Huaynaputina, 23.20 m, AD1601±1; Kuwae, 29.77 m, AD1460±5; Unknown (El Chichon?), 38.12 m, AD1259±5; Unidentified, 39.22 m, AD1228±5; Unknown, 41.52 m, AD1171±6.

2.2 Synchronisation onto GICC05 and INTCAL with ^{10}Be for the last 6 kyr

^{10}Be and ^{14}C are cosmogenic radionuclides, and their production rates are modulated by solar activity and by the strength of the Earth's magnetic field. Therefore ^{10}Be records in Greenland and Antarctica, as well as atmospheric ^{14}C reconstructions (INTCAL, Reimer et al., 2004) show common variations.

Three methods were used independently to construct age scales for EDC over the last 6 kyr. The first two are obtained by wiggle matching the EDML ^{10}Be record to either the GRIP ^{10}Be record dated by layer counting (GICC05, Vinther et al., 2006), or with the INTCAL atmospheric ^{14}C reconstruction (Reimer et al., 2004). These age scales have been transferred to EDC96 by volcanic synchronisation (Severi et al., 2007). The third time scale is obtained by wiggle matching to the Vostok ^{10}Be record with INTCAL atmospheric ^{14}C reconstructions (Raisbeck et al., 1998). The resulting Vostok age scale (more precisely the VK-BH1 core age scale) was then transferred to EDC96 via the VK-BH7 core by volcanic matching (Udisti et al., 2004).

We derive two age markers from these chronologies, at periods of large ^{10}Be and ^{14}C variations (when the synchronisation is robust). The three chronologies give similar ages within 30 years for these two periods and we calculated average ages of : 2716 yr BP and 5279 yr BP for the age markers at 107.83 m and 181.13 m, respectively.

[1]The identification of this volcanic eruption has actually been revised since the study by Castellano et al. (2005).

2.3 Match to GICC05 with CH_4 during the last deglaciation

During the last deglaciation, synchronisation to the NGRIP GICC05 chronology (Rasmussen et al., 2006) is possible with the transitions (Björck et al., 1998) that are common to the Greenland and Antarctic high resolution methane records, and the Greenland climate record (Severinghaus and Brook, 1999): GS-2a/GI-1e (Oldest Dryas/Bølling), GI-1a/GS-1 (Allerød/Younger Dryas) and GS-1/Holocene (Younger Dryas/Holocene). In that way an age for the CH_4 transitions can be obtained. This age for the gas record then has to be transferred to an age for the ice. However, the uncertainty in the estimation of this age difference (Δage) is large at EDC because of the low accumulation rate and the low temperature (typical model estimates of Δage at EDC are 2200 yr for the Holocene and 5500 yr for the LGM). This forces us to make a detour via the EDML ice core where accumulation rate and temperature are higher (typical model estimates of Δage at EDML are 700 yr for the Holocene and 1800 yr for the LGM). For the rapid warmings at the GS-2a/GI-1e and GS-1/Holocene transitions, the EDML CH_4 data were matched to the NGRIP stable isotope record (NGRIP project members, 2004). The corresponding GICC05 ages were transferred first from the EDML gas depth-scale to the EDML ice depth-scale by subtracting the calculated Δdepth (depth difference between gas bubbles and ice with the same age). Δdepth was obtained by multiplying the modelled close off depth (in ice equivalent, Loulergue et al., 2007) with the EDML mechanical thinning function (Huybrechts et al., 2007). This age was further transferred to EDC via the volcanic match between both cores (Severi et al., 2007).

The two derived age markers are 11.65±0.32 and 14.64±0.35 kyr BP for respectively 355.34 m and 421.15 m EDC96-depth. The uncertainty is estimated as the root mean square sum of the GICC05 age error (the number of uncertain layers given by Rasmussen et al., 2006, is taken as 2σ) and of a 300 yr 2σ uncertainty resulting from the uncertainty in the Δdepth estimate at EDML (2σ=10 m).

2.4 Match to GICC05 during the Laschamp event

The Laschamp geomagnetic excursion gives rise to a structured peak in the ^{10}Be records from Greenland (Yiou et al., 1997) and Antarctica (Raisbeck et al., 2002), which can be used to synchronise EDC96 to GRIP (Raisbeck et al., 2007), and in turn, to NGRIP dated by layer counting (GICC05, Andersen et al., 2006; Svensson et al., 2006). Two of the ^{10}Be sub-peaks have been localized in the EDC96 ice core at 735.35 m and 744.81 m, and at 2231.9 m and 2246.2 m at GRIP. The corresponding GICC05 age for the middle of these two peaks is 41 200 yr BP (max counting error of 1627 yr), corresponding to a depth of 740.08 m at EDC (Raisbeck et al., 2002) and we adopt this age.

This age of the Laschamp event is compatible (within the uncertainties) with K-Ar and ^{40}Ar-^{39}Ar ages from contemporaneous lava flow (40.4±2.0 kyr BP, Guillou et al., 2004). During this time period, which corresponds to D-O event 10 (Yiou et al., 1997; Raisbeck et al., 2002), GICC05 is also in good agreement with the Hulu Cave U-Th chronology (41.4 kyr BP, Wang et al., 2001), and with the Cariaco basin record (Hughen et al., 2004) when its ^{14}C ages are calibrated following the Fairbanks et al. (2005) curve (we obtain again an age of 41.2 kyr BP for the middle of the ^{10}Be peak corresponding to the middle of D-O 10). Genty et al. (2003) also found a compatible U-Th age of 40.0 kyr BP for the middle of D-O 10, though the identification of D-O 10 in this record is more ambiguous.

2.5 The Mont Berlin ash layer

Thanks to geochemical data (major elements and trace elements), Narcisi et al. (2006) identified a volcanic ash layer originating from a Mt Berlin (Antarctica) eruption. This event has been dated at 92.5±2 kyr BP by an Ar/Ar method applied on ash material collected close to the volcano.

2.6 Timing of termination II

The age of the rapid CH_4 event marking the end of termination II can be found by comparison to U-Th dated speleothem records, assuming that these fast transitions are synchronous. We obtain 129.3 kyr BP from Dongge cave in China (Yuan et al., 2004), and 130.9 kyr BP from Pekiin cave in Northern Israel (Bar-Matthews et al., 2003). We took the average of these two ages (130.1 kyr BP) and assumed a confidence interval of 2 kyr. We used the Δdepth estimate from the EDC2 age scale to export the CH_4 depth of 1723 m to an ice depth of 1699 m on EDC99. The uncertainty introduced by this ice/gas depth difference evaluation is only a few hundred years, so it is negligible compared to the uncertainty in the absolute age.

2.7 Air content age markers 0–440 kyr BP

The total air content of polar ice may be interpreted as a marker of the local summer insolation (Raynaud et al., 2007). Apparently, the solar radiative power absorbed at the surface influences the snow structure in the first upper meters and, in turn, the porosity of snow in the bubble close-off layer. The detailed physical mechanism is still under debate, however, the presence of a strong 41 kyr obliquity period in the air content signal makes it appropriate for the application of an orbital tuning method. We used 19 age markers from the air content age scale available back to 440 kyr BP. Each age marker corresponds to a minimum of obliquity, and the assumed uncertainty is 4 kyr[2].

2.8 $^{18}O_{atm}$ age markers for stages 300–800 kyr BP

A relationship between the isotopic composition of atmospheric oxygen ($\delta^{18}O$ of O_2, noted $\delta^{18}O_{atm}$) and daily northern hemisphere summer insolation has been observed at Vostok for the youngest four climate cycles. This property has been exploited to construct various orbital age scales for Vostok (Petit et al., 1999; Shackleton, 2000). Dreyfus et al. (2007) used a similar approach to derive an age scale for the bottom part of the EDC ice core (300–800 kyr BP) by assuming that $^{18}O_{atm}$ lags the summer-solstice precession variations by 5 kyr with an estimated uncertainty of 6 kyr. The selected age markers are placed at each mid-transition of $\delta^{18}O_{atm}$ (see Dreyfus et al., 2007, for more details).

2.9 The Brunhes-Matuyama reversal

The most recent of the geomagnetic inversions, referred to as the Brunhes-Matuyama reversal, has been localized between 3161 and 3170 m in the EDC ^{10}Be record (Raisbeck et al., 2006). This reversal has been dated radiometrically to have occurred 776±12 kyr BP (Coe et al., 2004), taking into account decay constant and calibration uncertainties. This transition has also been orbitally dated to be 778 kyr ago (Tauxe et al., 1996). Several authors have also reported evidence for a "precursor" event, 15 kyr before the B-M boundary (Brown et al., 2004), supported by the EDC ^{10}Be record.

3 Construction of the time scale

3.1 The EDC3 age scale

The EDC3 age scale was constructed in three stages.

First, a preliminary dating was obtained by ice flow modelling alone (Parrenin et al., 2007). The ice flow model has two components. 1) The initial annual layer thickness (i.e. the accumulation rate) is evaluated from the deuterium content of the ice, assuming an exponential relationship between accumulation rate and deuterium content, the later being corrected for variations in isotopic composition of the mean ocean. 2) The vertical compression of the layers, or total thinning ratio, is evaluated with a mechanical model. The age at a depth z is then given by:

$$\mathrm{age}\,(z) = \int_0^z \frac{1}{T\,(z')\,a\,(z')} dz'. \tag{1}$$

where $a(z)$ is the initial annual layer thickness and T(z) is the compression factor. This ice flow model contains several poorly known parameters: the average Holocene accumulation rate, the slope between deuterium and logarithm of accumulation, the basal melting, and two parameters for

[2] Since the definition of these air content age markers, the method to reconstruct a local insolation metronome based on the EDC air content record has been improved and the final air content age scale is slightly different.

the vertical profile of velocity (basal sliding and internal deformation). The values of these parameters have been determined by independent age markers, using a Monte Carlo Markov Chain (MCMC) inverse method. 21 age markers have been selected and are listed in Table 1. Not all those listed in Sect. 2 have been selected, in order to prevent overtuning the model in certain parts which would be a detriment to other parts. There are 8 age markers during the last climatic cycle, and in particular 3 during the Holocene. It is important to understand how this "modelled" age scale is dependent on these age markers. The average Holocene accumulation rate impacts the Holocene ages and is mainly constrained by the Holocene age markers (dated volcanoes and ^{10}Be age markers). Then the deuterium – accumulation slope affects the glacial ages and is mainly constrained by the age of the Laschamp event. The basal melting influences the total duration of the record and is mainly constrained by the bottom age markers. Finally, the two parameters related to the vertical profile of velocity only induce general trends in the age scale and are constrained by all the other age markers. Hence, the resulting age scale does not match perfectly the age markers obtained by comparison to insolation variations (obtained from the air content record).

The second stage is an a posteriori strict match of the age scale to dated volcanoes and to the NorthGRIP GICC05 time scale in the top part. In this part, the total thinning function is close to 1 and thought to be well constrained by the ice flow model. For this reason we expect the main sources of uncertainties to come from the accumulation model. Consequently we modified the modelled accumulation rate so that the resulting age scale fits perfectly with: 1) the dated volcanoes of the last millenium; 2) the two ^{10}Be age markers in the last 6 kyr (Sect. 2.2); 3) one methane age marker during the last deglaciation (Sect. 2.3); 4) the Laschamp age marker at 41.2 kyr BP (Sect. 2.4). These age markers are listed in Table 1.

The third stage is a correction of the modelled thinning function in the bottom 500 m of the core (beyond MIS11, ~400 kyr BP), where the ice flow model is unable to fit the $\delta^{18}O_{atm}$ age markers (Dreyfus et al., 2007). This problem was first detected by Lisiecki and Raymo (2005), who suggested a problem in the accumulation estimate. However, Dreyfus et al. (2007) showed, by a comparison of deuterium and CO_2 variations, that this anomaly is principally due to the presence of ice flow irregularities. They a posteriori corrected the total thinning function so that the resulting age scale fits those $\delta^{18}O_{atm}$ age markers within their confidence interval. See Dreyfus et al. (2007, Table 1) for a complete list of the age markers used and for more details on the method.

By following this procedure, we have used the best available chronological information for each section of the core, while still allowing the model to provide a smooth interpolation of all unconstrained periods.

As stated in the introduction, two different cores have been drilled at EDC: EDC96 extending to 788 m depth (approxi-

Table 1. Age markers used for the construction of the EDC3 age scale. They fall into 3 categories: 1) Age markers used to control the poorly known parameters of the modelling; 2) Age markers used for a posteriori correction in the top part of the core (EDC3 is required to pass exactly through those age markers); 3) Age markers used to correct for ice flow anomalies in the bottom part.

age marker	depth (m)	age (kyr BP)	error bar (kyr BP)	model control	top correction	bottom correction
Krakatua	8.35	0.066	0.001		X	
Tambora	12.34	0.134	0.001		X	
Huaynaputina	23.20	0.349	0.001		X	
Kuwae	29.27	0.492	0.005		X	
El Chichon?	38.12	0.691	0.005	X	X	
Unidentified	39.22	0.722	0.006		X	
Unknown	41.52	0.779	0.006		X	
^{10}Be/^{14}C	107.83	2.716	0.05	X		
^{10}Be/^{14}C	181.12	5.28	0.05	X	X	
YD/Holocene	361.5	11.65	0.18	X		
PB/BO	427.2	15.0	0.24	X	X	
^{10}Be peak	740.08	41.2	1	X	X	
Mt Berlin erupt.	1265.10	92.5	2	X		
term. II	1698.91	130.1	2	X		
air content	1082.34	70.6	4	X		
air content	1484.59	109.4	4	X		
air content	1838.09	147.6	4	X		
air content	2019.73	185.3	4	X		
air content	2230.71	227.3	4	X		
air content	2387.95	270.4	4	X		
air content	2503.74	313.4	4	X		
air content	2620.23	352.4	4	X		
air content	2692.69	390.5	4	X		
air content	2789.58	431.4	4	X		
$^{18}O_{atm}$	2714.32	398.4	6			X
$^{18}O_{atm}$	2749.04	408.6	6			X
$^{18}O_{atm}$	2772.27	422.0	6			X
$^{18}O_{atm}$	2799.36	441.0	6			X
$^{18}O_{atm}$	2812.69	454.3	6			X
$^{18}O_{atm}$	2819.2	464.6	6			X
$^{18}O_{atm}$	2829.36	474.8	6			X
$^{18}O_{atm}$	2841.75	485.3	6			X
$^{18}O_{atm}$	2856.27	495.9	6			X
$^{18}O_{atm}$	2872.56	506.6	6			X
$^{18}O_{atm}$	2890.33	517.6	6			X
$^{18}O_{atm}$	2913.3	532.0	6			X
$^{18}O_{atm}$	2921.99	545.3	6			X
$^{18}O_{atm}$	2938.24	556.4	6			X
$^{18}O_{atm}$	2968.08	567.6	6			X
$^{18}O_{atm}$	2998.96	578.6	6	X		X
$^{18}O_{atm}$	3008.93	589.5	6			X
$^{18}O_{atm}$	3017.25	600.1	6			X
$^{18}O_{atm}$	3027.54	610.9	6			X
$^{18}O_{atm}$	3035.41	622.1	6	X		X
$^{18}O_{atm}$	3043.01	634.4	6			X
$^{18}O_{atm}$	3048.51	649.1	6			X
$^{18}O_{atm}$	3056.77	660.8	6			X
$^{18}O_{atm}$	3065.93	671.7	6			X
$^{18}O_{atm}$	3077.74	682.3	6			X
$^{18}O_{atm}$	3093.51	693.2	6			X
$^{18}O_{atm}$	3112.43	704.0	6			X
$^{18}O_{atm}$	3119.57	714.4	6			X
$^{18}O_{atm}$	3124.27	724.4	6			X
$^{18}O_{atm}$	3136.18	733.9	6			X
$^{18}O_{atm}$	3143.2	741.9	6			X
$^{18}O_{atm}$	3152.25	749.2	6			X
$^{18}O_{atm}$	3158.91	758.1	6			X
$^{18}O_{atm}$	3166.87	767.7	6			X
$^{18}O_{atm}$	3174.81	777.6	6			X
$^{18}O_{atm}$	3180.6	787.7	6			X
$^{18}O_{atm}$	3189.83	797.5	6			X
B-M reversal	3165	785	20	X		

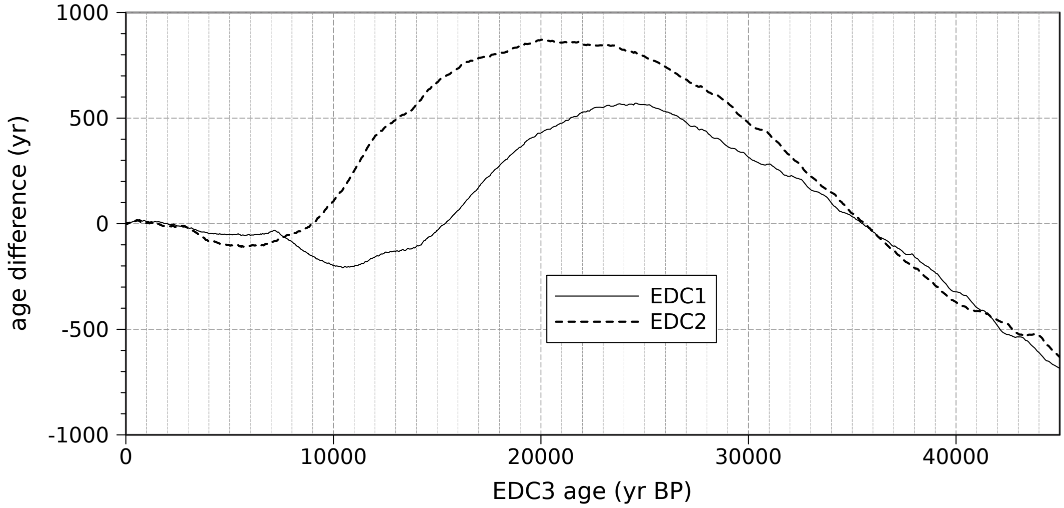

Fig. 1. Age difference between the EDC1 (resp. EDC2) and EDC3 time scales for the last 45 kyr.

mately back to 45 kyr BP), and EDC99 drilled down to the bedrock. For the first ∼45 kyr, the majority of paleoclimatic reconstructions have been obtained from EDC96. Therefore, EDC3 has been defined on EDC96 depths on the shallow part and on EDC99 depths in the bottom part. The age scale has then been transferred to EDC99 in the shallow part thanks to a volcanic synchronisation of the two cores (Wolff et al., 2005).

Estimates of the gas-ice age difference and related discussions can be found in Loulergue et al. (2007).

3.2 EDC3 exported to EDML, Dome Fuji and Vostok

The EDC3 age scale was then exported to EDML, Dome Fuji and Vostok thanks to synchronisation of these ice cores with EDC. The EDC-EDML synchronisation and the resulting EDML1 chronology are fully described in Severi et al. (2007) and Ruth et al. (2007). The EDC-DF and EDC-VK synchronisations are done by matching isotopic records, and by using common volcanic horizons (Narcisi et al., 2005[3]). See supplementary material (http://www.clim-past.net/3/485/2007/cp-3-485-2007-supplement.zip) for a list of synchronisation markers used.

4 EDC3 compared to other age scales

4.1 Comparison with EDC1 and EDC2

The former EDC1 time scale for EDC96 (Schwander et al., 2001), and the extended EDC2 for the last 740 kyr (EPICA community members, 2004) were also built on a combination of age markers and modelling information. As for EDC3, a one dimensional ice flow model was controlled by a set of age markers. There are however several important differences. For EDC1, the time scale extended only back to 45 kyr BP, and different glaciological parameters were used for different time periods covered by the time scale. EDC2 extended only back to 740 kyr BP and there was no a posteriori correction of the age scale, neither in the top part, nor in the bottom part where the ice flow is complex. Moreover, the ice flow model did not take into account basal sliding and variations in ice sheet thickness, and the age markers were mainly obtained by comparison to the oceanic Bassinot stack (Bassinot et al., 1994).

Figure 1 compares EDC1 and EDC3 on the last 45 kyr. EDC2 is also shown for convenience, but EDC1 was still the official age scale for the top part of the core. EDC3 is younger by a few decades for the last 2 kyr. Then it is older by less than 100 yr between 2 and 8 kyr BP. The difference increases to ∼200 yr for the early Holocene period, around 10 kyr BP. Then the difference becomes positive (EDC1 is older) with a maximum of ∼600 yr at the LGM. The difference finally decreases roughly linearly down to –700 yr at 45 kyr BP.

Figure 2 compares EDC2 and EDC3. The difference ranges approximately between –1.5 and +3 kyr for the last 400 kyr. EDC3 is older during the last glacial period, with a difference of ∼3 kyr for MIS 5.5. This is due in particular to the use of the Mt Berlin and Termination II age markers. The difference between EDC3 and EDC2 then slowly decreases back to MIS 10.

For the period 400–800 kyr BP, the difference is much larger, and reaches –20 and +7 kyr. This is due to the a posteriori correction in EDC3 of ice flow irregularities in the bottom part of the core. The largest differences are for MIS

[3]We did not use the EDC-VK volcanic synchronisation obtained by Udisti et al. (2004), because it concerns the 5G VK core, and not the 3G core on which the deuterium measurements have been performed.

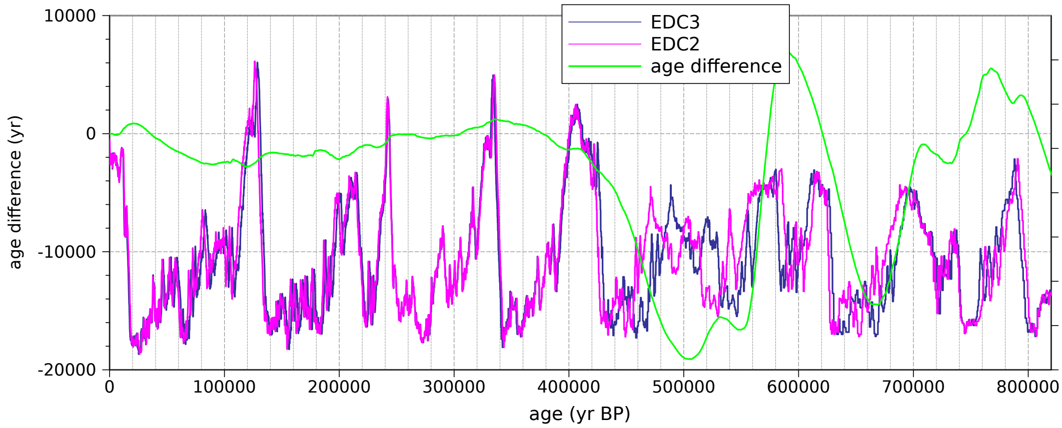

Fig. 2. Comparison of the EDC deuterium record on the EDC2 and EDC3 time scales. The green curve represents the difference in age between EDC2 and EDC3. Y-axes for isotopic records are normalised.

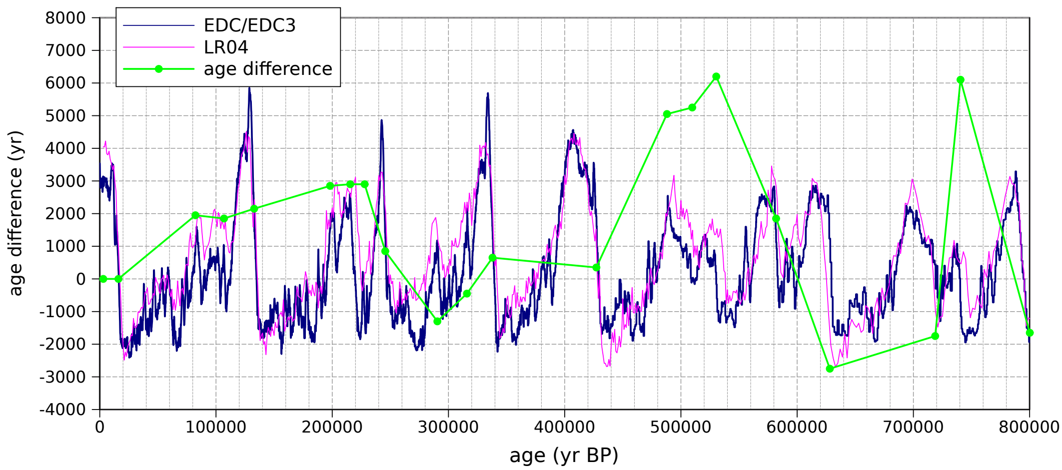

Fig. 3. Comparison of the EDC deuterium record on the EDC3 time scale with the LR04 marine stack on its own time scale, shifted by 3 kyr towards older ages. The green curve represents the difference in age between LR04 (+3 kyr) and EDC3 assuming both records are synchronous. Y-axes for isotopic records are normalised.

13–14 (where EDC3 is older by 15–20 kyr), MIS 15.3 (where EDC3 is younger by ∼5 kyr) and MIS 16 (where EDC3 is older by 10–15 kyr). Duration of MIS 15.1 has been considerably shortened in EDC3, while the duration of MIS 12 is now longer.

4.2 Comparison with LR04

The LR04 marine stack is composed of benthic δ^{18}O records from 57 globally distributed sites aligned by an automated graphic correlation algorithm (Lisiecki and Raymo, 2005). The LR04 age model is derived from tuning the δ^{18}O stack to a simple ice model based on 21 June insolation at 65° N, with additional constraints from the sedimentation to prevent overtuning.

In Fig. 3, we compared the EDC deuterium record on EDC3 with the LR04 stack on its own time scale. Of course, as a benthic record, LR04 contains a sea level part and a temperature part and as a consequence is older than EDC by several thousands of years. For an easier comparison, we thus shifted it by 3 kyr towards older ages. This 3 kyr phase is the observed phase of both records during the last deglaciation. On Fig. 3 is also plotted the age difference between the two age scales (with the 3 kyr phase lag removed). For that, we used features that can be identified with confidence in both curves (e.g. terminations). We preferentially placed points at mid-transitions.

The overall agreement between both time scales is good, with differences never exceeding 6 kyr. In contrast, the previous EDC2 time scale showed disagreements up to 20 kyr with LR04 in the part older than 400 kyr BP (Lisiecki and Raymo, 2005; Dreyfus et al., 2007). The age difference is particularly small during the last 400 kyr (back to MIS11),

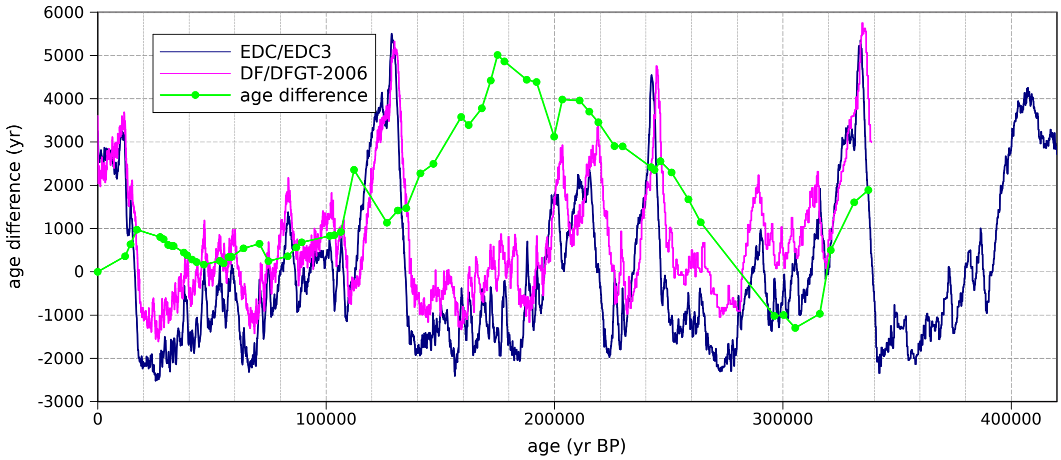

Fig. 4. Comparison of the EDC deuterium record on the EDC3 time scale with the Dome Fuji δ^{18}O record on the DFGT-2006 time scale (Parrenin et al., 2007). The green curve represents the difference in age between DFGT-2006 and EDC3 at the depth of the synchronisation markers. Y-axes for isotopic records are normalised.

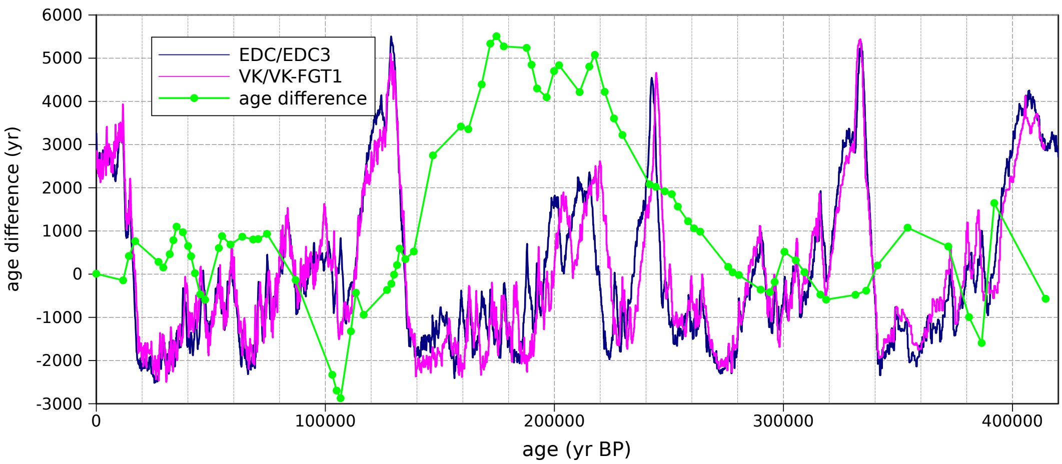

Fig. 5. Comparison of the EDC deuterium record on the EDC3 time scale with the Vostok deuterium record on the VK-FGT1 time scale (Parrenin et al., 2004). The green curve represents the difference in age between VK-FGT1 and EDC3 at the depth of the synchronisation markers. Y-axes for isotopic records are normalised.

oscillating between –1.5 kyr and 3 kyr. This age difference may reflect either errors in the synchronisation, or may be due to phases in the climatic system, i.e. related to the fact that both curves do not represent the same climatic proxy. The fact that this difference is stable is reassuring because it shows a certain consistency between both time scales which were derived completely independently. The glaciological modelling method thus seems appropriate for Dome C back to MIS11 without any additional distortion. The age difference increases to approximately 6 kyr between 450 and 600 kyr BP, then reaches its minimum at termination VII (from MIS16 to MIS15) with –3 kyr, increases again to 6 kyr at MIS18, and finally decreases to around –2 kyr at termination 9 (from MIS20 to MIS19). This bottom interval (beyond MIS11) where the age difference is less stable, is where the ice flow model becomes inaccurate (Dreyfus et al., 2007).

4.3 Comparison with DF and VK glaciological chronologies

In Fig. 4 and Fig. 5, we compare the EDC isotopic record on the EDC3 time scale with the Dome Fuji and Vostok isotopic record, on their respective glaciological age scales DFGT-2006 (Parrenin et al., 2007) and VK-FGT1 (Parrenin et al., 2004).

The age differences are always less than 1 kyr for the last ~90 kyr. This good agreement is especially remarkable because very few age markers were used for the last glacial part. We interpret it as the fact that the glaciological models used are robust for the upper part of the ice sheets where the mechanical ice flow is still predictable. It is also a proof that the assumed relationship between isotopic content of the ice and surface accumulation rate is valid within a few percent.

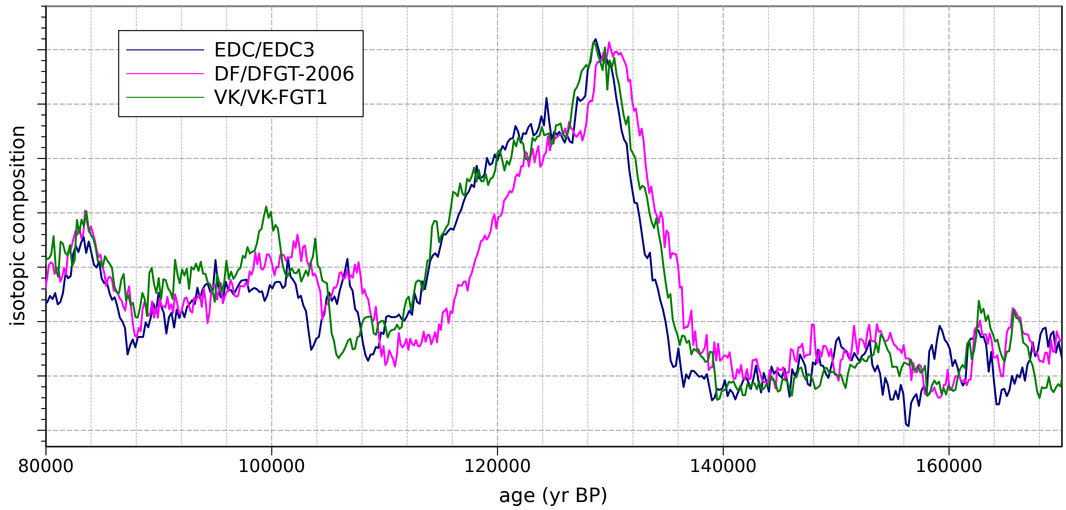

Fig. 6. Comparison of three glaciological age scales during the time interval MIS6-MIS5.4. The EDC deuterium record is on the EDC3 time scale. The Vostok deuterium record is on the VK-FGT1 time scale (Parrenin et al., 2004). The Dome Fuji δ^{18}O record is on the DFGT-2006 time scale (Parrenin et al., 2007). Y-axes for isotopic records are normalised.

The age of term. II is roughly consistent in all three glaciological chronologies, as can be seen in Fig. 6. Using the rapid methane event marking the end of the deglaciation and corresponding to the end of the Antarctic isotope increase, we obtain 129.2 kyr BP in EDC3, 129 kyr BP in VK-FGT1 and 129.8 kyr BP in DFGT-2006. This age is also in good agreement with estimates based on coral-reef high stands (Waelbroeck et al., 2007[4]). The age old debate on the age of Termination II, old in a previous ice core chronology (Lorius et al., 1985) and young in the orbitally tuned marine records (Imbrie et al., 1984) now seems to be converging.

The age discrepancies are larger for the second climatic cycle, where EDC3 is significantly older than both DFGT-2006 and VK-FGT1, the difference reaching around 5 kyr. The agreement is again better for the third and fourth climatic cycles, with differences never exceeding 2 kyr.

Figure 7 compares the duration of climatic events in EDC3 and DFGT-2006, or in EDC3 and VK-FGT1. These three time scales are consistent, generally within 20%. It should be noted that differences depicted on this figure may either reflect a real difference in the age scales, or an error in the synchronisation process. The agreement is very good back to ∼90 kyr BP, but then the situation for MIS5.4 to 6 is more complex (see Fig. 6). MIS5.4 is significantly shorter in EDC3 than in DFGT-2006 and VK-FGT1. Then, the duration of MIS5.5 (∼16 kyr, taken at mid-transitions) is intermediate in EDC3 between its duration in DFGT-2006 (∼14.5 kyr) and its duration in VK-FGT1 (∼18 kyr). Finally, the duration of MIS6 is significantly shorter in EDC3 than in both other age scales. We do not know at this stage if these discrepancies are due to poorly understood processes in the accumulation models or in the mechanical thinning models. A recent study on the structure of cristallographic orientations suggests non-unidimensional flow processes for this time period (Durand et al., 2007), and the authors suggest accurately monitoring the EDC borehole to quantify the amount of shear. A precise synchronisation between the ice cores in both the ice and gas phases may also help distinguish an accumulation anomaly from a thinning anomaly.

[4]Waelbroeck, C., Frank, N., Jouzel, J., Parrenin, F., Masson-Delmotte, V., and Genty, D.: Transferring radiometric dating of the Last Interglacial sea level high stand to marine and ice core records, submitted, 2007.

5 Confidence interval of the age scale

The confidence interval determination is a difficult task when no robust statistical information is available. Here, we evaluate it subjectively by using the comparison with the other age scales and with the age markers.

Back to AD1600, the error in EDC3 mainly comes from the interpolation of the dated volcanoes which we estimate it to be 3 yr (2σ). Between AD1100-1600, the age error of the volcanoes increases to 5 yr, and adding an interpolation error we estimate the total error at 8 yr. The accuracy is then constrained by the accuracy of the ^{10}Be age markers, which we estimate at 100 yr. We thus estimate that the 2σ error on EDC3 increases to 100 yr at 2000 yr BP and stays stable back to 6000 yr BP. The accuracy of EDC3 then increases to 400 yr at 14 kyr BP, which is roughly the error on the CH_4 age markers. By comparison to the Dome Fuji and Vostok chronologies and to the GICC05 age of the Laschamp, we estimate the confidence interval to increase to 1 kyr at 18 kyr (Last Glacial Maximum), 1.5 kyr at 40 kyr, and finally

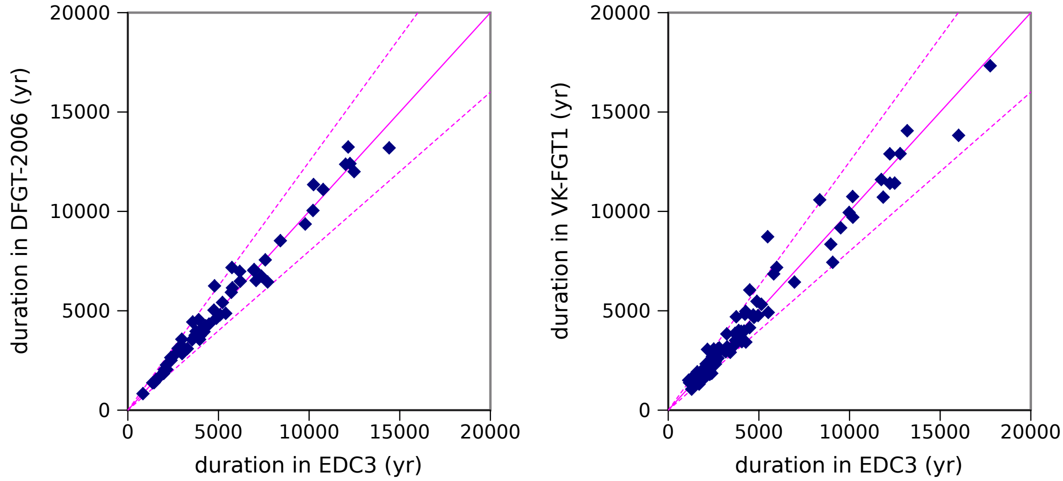

Fig. 7. Durations between two consecutive synchronisation markers in EDC3 compared to durations in DFGT-2006 (left panel) or in VK-FGT1 (right panel). Plain pink line is the 1:1 curve. Dashed pink lines represent the 1:0.8 and 0.8:1 lines.

3 kyr at 100 kyr BP. Our estimated confidence interval is constrained by the quality of the orbital tuning age markers from air content or $^{18}O_{atm}$ records; we estimate it to increase to 6 kyr at 130 kyr and to stay stable down to the bottom of the record.

In terms of event durations, we estimate the accuracy to be 20% for the top part of the record (back to MIS11), by comparison to Vostok and Dome Fuji glaciological age scales. For the bottom part (below MIS11), a more conservative estimate of 40% is more appropriate because of the flow anomalies (Dreyfus et al., 2007).

6 Conclusion and perspectives

We derived an EDC3 chronology for the EPICA Dome C ice core, which was then exported to EDML, Dome Fuji and Vostok ice cores by synchronisation of these ice cores. This chronology has been obtained using a combination of age markers and ice flow modelling. The good agreement between EDC, Vostok and Dome Fuji ice flow models points to the good accuracy of EDC3 in terms of event durations, which we estimate to be better than 20% for the last 400 kyr. This is a significant improvement with respect to marine age scales where the resolution is poorer and where the sedimentation is less regular.

Apart from ice flow modelling improvements, further developments need to be done concerning the inverse method used for the conjunction of models and age markers. The method used for EDC3 is based on a so-called deterministic approach, where the uncertainties in the ice flow models are supposed to originate from poorly known physical parameters. In reality, there are other non-identified sources of uncertainty in these models which need to be taken into account in a statistical way. A second potential improvement is to apply this inverse method to several drilling sites simultaneously, to obtain a common and optimal age scale for several ice cores, as has been done in the marine world (Lisiecki and Raymo, 2005).

We also hope that the precision of the age markers will increase in the coming years. The number of U-Th dated speleothems for the last climatic cycles should increase in the future (Henderson, 2006). New local insolation proxies such as O_2/N_2 and air content are also a promising source of accurate age markers, but the physical mechanisms involved need to be better understood and the accuracy of these age scales needs to be independently confirmed.

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